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Analysis of implementing phase change materials in open-air swimming pools

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Abstract

Open-air swimming pools in Mediterranean climate regions are heated by direct solar radiation with no auxiliary heating systems. In order to extend the swimming season or improve comfort conditions, solar collectors or pool coverings may be used. In this paper, another approach was followed through the use of phase change materials (PCM). Two methods of introducing the PCM were considered: (1) encapsulated in the sidewalls and bottom of the pool, and (2) use the PCM in an external heat exchanger. Heat is stored when water temperature is sufficiently high, while it is released when water temperature drops below comfort levels. A numerical model was built and validated for predicting the evolution of the water temperature, by taking into account meteorological data at three different locations in north-east of Spain. The simulations showed that using phase change materials provided some improvement of water conditions, especially when used in an external heat exchanger.

Keywords: Open-air swimming pool; Phase change material; Energy savings; Latent heat; Thermal inertia

1. Introduction

Usually, open-air swimming pools are naturally heated by direct solar radiation incident to the water surface, and also by convection from the ambient air, if its temperature is higher than water temperature. Because of the intermittent character and seasonal and meteorological conditions, water temperature only achieves comfortable levels in certain conditions and for limited periods of time. If one wishes to extend the bath season or improve comfort conditions, one needs an auxiliary source of energy, besides the direct solar energy gain. In Spain, open-air swimming pools are not allowed to be heated using fossil fuel (Spanish Standard, 2007), so if there is a need for extra heating during some period, one has to think on alternative solutions. To achieve a higher water temperature, one can either increase the amount of energy that is transmitted to the pool, and/or reduce energy losses by evaporation, radiation and convection to the ambient air. The most common and efficient ways of doing that is implementing solar collectors as an extra energy source, and also pool covering during the periods when the swimming pool is not used (Czarnecki, 1963; Francey et al., 1980; Haaf et al., 1994; Hahne and Kübler, 1994; Molineaux et al., 1994; Rakopoulos and Vazeos, 1987; Szeicz and McMonagle, 1983; Yadav and Tiwari, 1987).

Small swimming pools for residential buildings are very common in Mediterranean climate regions and, normally, do not need extra heating during summer months, specially in July and August. Out of this period, during the months of May, June and September, ambient conditions can be appropriate for using the swimming pool, but a comfortable water temperature is not always accom-

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Nomenclature

A_p	pool area (m^2)
a	coefficient in Eq. (10)
b	coefficient in Eq. (10)
A	coefficient in Eq. (14)
B	coefficient in Eq. (14)
c	specific heat ($J\ kg^{-1}\ C^{-1}$)
G	irradiance ($W\ m^{-2}$)
h_{eva}	evaporative heat transfer coefficient ($W\ m^{-2}\ Pa^{-1}$)
h	convective heat transfer coefficient ($W\ m^{-2}\ C^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ C^{-1}$)
m	mass flow rate
n	exponent in Eq. (10)
P	pressure (Pa)
Q	heat flow rate (W)
T	temperature (°C, K)
U	global heat transfer coefficient ($W\ m^{-2}\ C^{-1}$)
V	volume (m^3)
w	wind speed ($m\ s^{-1}$)

Greek

α	absorptance
ε	emissivity
ε_{he}	efficiency of heat exchanger
ρ	density ($kg\ m^{-3}$)
σ	Stefan–Boltzmann constant

Subscripts

amb	ambient
bott	bottom
conv	convection
eva	evaporation
he	heat exchanger
melt	melting
p	pool
rad	radiation
reg	registered
sat	saturated
sim	simulated
sol	solar
tot	total
v	vapour
w	water

Abbreviations

HE	heat exchanger
PCM	phase change material

plished if no auxiliary heating system is used. Cusido and Puigdomenech (1986) designed and built a system consisting of efficient and low-cost solar collectors, with an installed collecting area of 11 m^2, for heating a small residential swimming pool in an open circuit. The experimental system, located in Palafrugell at a latitude of 42° north in the north-east end of Spain, was able to prolong the usage period of the pool up to 6 month a year.

An experimental analysis of a real swimming pool in the neighbourhood of Alicante, Spain, was conducted by Ruiz and Martínez (2010). In their work, a TRNSYS model of a private open-air pool is validated by experimental measurements of the water temperature evolution, taking into account *in situ* meteorological data. In their study they consider solar collectors as a source of additional energy for heating the pool, as an option to extend the swimming season, and investigate the effect of the absorber field size on the thermal behaviour of the swimming pool.

Phase change materials (PCM) are used in many different applications, taking the advantage of their capacity of absorbing or releasing energy in the form of latent heat during the melting or solidifying process, respectively (Farid et al., 2004; Mehling and Cabeza, 2008; Zalba et al., 2003). Applications using PCM can be classified into two main groups: thermal inertia and heat storage. For the first group of applications, the PCM is used as protection against undesirable fast variations of the heat transfer rate, in which case low thermal conductivity of the PCM is desirable. For the second group of applications, on the contrary, a higher PCM conductivity is required in order to store or extract the heat into or from the storage system. Regardless of the specific application, one of the main goals of using PCM is to improve human comfort conditions without a consequent increase in energy consumption, by making use of clean sources of energy such as renewable or waste energies.

In applications where there is a shift between heat demand and supply or availability, the use of a thermal energy storage systems based on PCM represent a simple and efficient way in which this non-coincidence problem can be improved or even solved.

A potential application, for which a PCM storage energy system may be used, is for open-air swimming pools.

In the case of outdoor swimming pools, there is coincidence between energy demand and supply, since they are heated by direct solar energy during day-time, and is precisely during this period of the day when people swim. Nevertheless, one may consider the possibility that, under certain circumstances, a non-coincidence might exist between the temperature peaks of ambient air and water in the swimming pool. This may occur after a period of

hot weather conditions followed by a sudden drop of the ambient temperature, which implies a drop in the water temperature, at a rate that depends on the size and geometry of the pool. While ambient temperature may have a relatively rapid recuperation time, water may still remain too cold for bath. If this is the case, one may consider improving water comfort conditions, by implementing a PCM energy storage system. The main idea of using a PCM storage system in an open-air swimming pool is that of accumulating latent heat when there is sufficient direct solar radiation and the water temperature is at levels of comfort or above, and release this stored energy after periods of poor solar radiation. This can avoid the water in the pool to become too cold for bath, and keep it in the range of comfort. As a consequence, one is able to prolong the total period of the swimming pool usage by increasing the number of days proper for bath, especially at the beginning or at the end of summer.

The main objective of this work is to simulate the thermal behaviour of the water in open-air swimming pools in the presence and absence of a PCM storage system, and to study the effects it has in improving comfort conditions with respect to the case of no auxiliary system usage. This task requires the use of weather data, such as solar radiation, ambient temperature, wind speed and relative humidity of air. It also requires the use of correlation available in the literature to predict energy losses due to evaporation, radiation, convection, etc.

The simplified modelling approach followed in this work is used to test the benefit of using a PCM storage system. The model will be validated using some published experimental measurements. The effect of using solar collectors and covering systems, which has been studied before, is not part of this study, but their effect can be incorporated in the model. To our knowledge, such a study has not been done before.

2. Methodology

The evolution of water temperature in a pool with a surface area of 50 m^2 and a mean depth of 1.65 m was predicted using a numerical model, by taking into account four meteorological parameters: ambient temperature, wind speed, relative humidity and solar irradiance. The experimental data registered by Ruiz and Martínez (2010) was used for model validation. The model was then used to predict the evolution of the water temperature for three distinct locations in the north-east of Spain. The weather data used in the model come from measurements done at 2 m elevation from the ground and at intervals of 1 h.

2.1. Swimming pool with PCM

The system analysed in this paper is a small swimming pool of rectangular form, with the following dimensions: 10 m long × 5 m width × 1.65 m height. This gives a total volume of 82.5 m^3 of water. A 3 cm layer of PCM was assumed to be covering the walls and bottom surfaces of the pool, in thermal contact with the water by natural convection. The choice of this value for the thickness of the PCM layer is discussed below in Section 3.5. The way PCM is encapsulated is not discussed in this paper, but there are many possibilities of micro and macro encapsulation.

Another way for implementing PCM in the pool was through an external heat exchanger containing PCM having the same or different melting point. This heat exchanger is connected to the filter circuit of the pool and can be switched on or off as required. The advantage of using such a heat exchanger is that it can store latent heat when water is warm enough, and give it back to the pool only when it is needed. The time when the heat exchanger should be switched on is related to the weather forecast. When a period is predicted, of a few consecutive days with weather conditions suitable for bath, the heat exchanger should be switched on some time before bath, so that it has sufficient time to release a considerable amount of heat to the water. The precise instant of switch on depends on the efficiency of the heat exchanger and also on the water temperature and PCM melting point. For the simulations done in this work, the switch on time is about 20 h before the time corresponding to the first peak in the water temperature of the forthcoming bath period.

2.2. Modelling of the swimming pool

In order to simulate thermal behaviour of the swimming pool, the Engineering Equation Solver (EES) software was used. The pool was assumed to undergo sufficient mixing so that a single node representing pool temperature was considered. Even though such assumption may not be very realistic, it is good enough for the objective of this paper to show the effect of using PCM in a swimming pool. The temperature of the pool can be determined from the energy balance Eq. (1), which is solved by finite difference method:

$$V_p \cdot \rho_w \cdot c_w \cdot (dT_p/dt) = Q_{total} \tag{1}$$

where Q_{total} includes all the energy fluxes that are entering and leaving the pool (see Fig. 1):

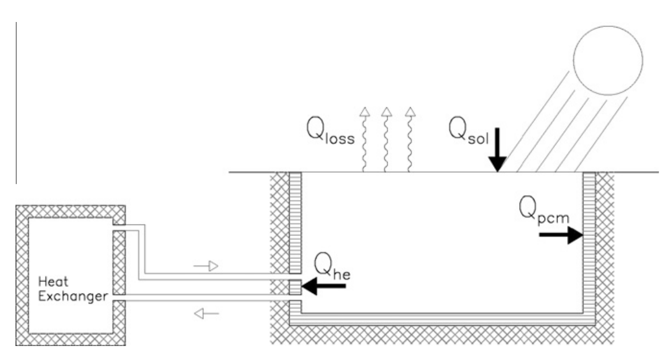

Fig. 1. Heat flow-rates on an open-air swimming pool with PCM encapsulated in the sidewalls and bottom, connected to a heat exchanger.

$$Q_{total} = Q_{sol} - Q_{loss} - Q_{pcm} - Q_{he} \tag{2}$$

The term Q_{loss} consists of the sum of the heat losses due to evaporation, radiation and convection, see Eq. (3). Other kinds of heat losses, such as conduction to the ground, rain water or fresh water supply, were ignored because they are small enough in comparison to the other:

$$Q_{loss} = Q_{eva} + Q_{rad} + Q_{conv} \tag{3}$$

The term Q_{pcm} in Eq. (2) represents the heat transferred to the PCM located in the walls and at the bottom of the pool. Although this term has a negative sign in Eq. (2), it may account for a heat loss or gain of the water, depending on the temperatures difference of water and PCM:

$$Q_{pcm} = h_s \cdot A_s \cdot (T_p - T_{pcm,s}) \tag{4}$$

where the subscript s accounts for the surface of the wall or bottom. The values of the convection heat coefficients h_{wall} and h_{bott} are inferred by using the corresponding procedures available in the EES software for free convection between a fluid and a vertical or horizontal surface, respectively. These procedures have as input variables the fluid name, the surface temperature, the bulk temperature of the fluid, the ambient pressure and the characteristic length of the surface. In the case of the wall surface, the characteristic length is its height, while in the bottom surface case its characteristic length is the ratio between its area and its perimeter.

To simulate the heat flux through the PCM layer, 20 nodes were used. The temperature $T_{pcm,s}$ is the temperature of PCM surface in thermal contact with the water, i.e., the temperature of the first node. The energy balance equation for the internal node i is:

$$\frac{\rho_{pcm} \cdot c_i \cdot \Delta s}{\Delta t} \cdot (T_i^s - T_{i,old}^s) = \frac{k_{pcm}}{\Delta s} \cdot (T_{i-1}^s - T_i^s) + \frac{k_{pcm}}{\Delta s} \cdot (T_{i+1}^s - T_i^s) \tag{5}$$

where Δs is the distance between two consecutive nodes and Δt is the time step. The values used for the PCM density ρ_{pcm} and thermal conductivity k_{pcm} are shown in Table 1. In Eq. (5), c_i represents the specific heat of the PCM corresponding to the temperature T_i of the node i. The simplified analytical dependence of the effective specific heat capacity of PCM on temperature is defined by the following equation:

$$c_i = \begin{cases} 1500 \text{ for } T \leqslant T_{melt} - 3 \text{ or } T \geqslant T_{melt} + 1 \\ 28{,}500 \cdot (T - T_{melt} + 3) + 1500 \text{ for } T_{melt} - 3 < T < T_{melt} \\ -85{,}500 \cdot (T - T_{melt} - 1) + 1500 \text{ for } T_{melt} \leqslant T < T_{melt} + 1 \end{cases} \tag{6}$$

where c_i is in J/kg C and T_{melt} is the melting or solidifying temperature of PCM. This gives a total latent heat of 177 kJ/kg, which is a common value for a typical PCM (Farid et al., 2004; Zalba et al., 2003).

In the case in which an external PCM heat exchanger is used for thermal storage (see Fig. 1), the term Q_{he} in Eq. (2) accounts for the heat flux received by the heat exchanger (Holman, 1992):

$$Q_{he} = m_w \cdot c_w \cdot \varepsilon_{he} \cdot (T_p - T_{he}) \tag{7}$$

where m_w is the water mass flow rate through the filter circuit, and T_{he} is the melting point of the PCM in the heat exchanger. The amount of PCM that should be charged in the external heat exchanger is similar to the previous case, in which PCM is located in the walls and bottom of the pool. A mass of 4250 kg of PCM was considered in this case, which gives a total storage capacity in the form of latent heat of around 7.5×10^8 J for the heat exchanger. The efficiency of the heat exchanger, ε_{he}, can be determined from the equation (Holman, 1992):

$$\varepsilon_{he} = 1 - \exp(-U_{he} \cdot A_{he}/(m_w \cdot c_w)) \tag{8}$$

with U_{he} being the global heat transfer coefficient and A_{he} the heat exchanger surface area. The values used for the parameters appearing in Eq. (8) are shown in Table 1.

2.3. Empirical correlations used to predict heat transfer coefficients

In this section, the empirical correlations found in the literature, describing the different heat flow rates involved in the swimming pool analysis, are presented. They are expressed in terms of measurable or estimated properties such as meteorological conditions or water temperature.

2.3.1. Evaporative losses

Evaporative losses on water surface may be described by the following equation:

$$Q_{eva} = h_{eva} \cdot A_p \cdot (P_{v,sat} - P_{v,amb}) \tag{9}$$

where $P_{v,sat}$ is the saturated vapour pressure at water temperature and $P_{v,amb}$ is the vapour pressure in the ambient air. The evaporative heat transfer coefficient h_{eva} takes the form:

$$h_{eva} = a + b \cdot w^n \tag{10}$$

Ruiz and Martínez showed a comparison between the correlations obtained by Smith et al. (1994), ASHRAE (2003), Richter (1979), ISO TC 180 (1995), Rohwer (1931) and McMillan (1971). They also compared these correlations with their experimental results and concluded

Table 1
Parameter values related to the PCM and the external heat exchanger.

ρ_{pcm} (kg m^{-3})	k_{pcm} (W m^{-1} C^{-1})	$U_{he} \cdot A_{he}$(W C^{-1})	m_w (kg s^{-1})
1460	0.6	6000	0.955

Table 2
Constants for Eq. (10) of evaporation rate correlation.

	a (W m^{-2} Pa^{-1})	b (W s$^{1/2}$ m$^{-5/2}$ Pa^{-1})	N
Value	0.0423	0.0565	0.5

that the correlation proposed by Richter (1979) shows best agreement. Based on that, the values shown in Table 2 for the constants a, b and n were used in this paper.

The parameter w represents the wind speed at a location close to the water surface, and its value depends on the location of the measuring instruments, or the landscape of the pool surroundings. In the investigations done by Richter (1979), wind speed was measured at 0.5 and 2 m height above the surface of a lake, in good agreement with the data used in this work, which has been registered at a height of 2 m.

2.3.2. Radiative losses

Radiation losses can then be expressed in terms of the sky and water temperatures:

$$Q_{rad} = A_p \cdot \varepsilon \cdot \sigma \cdot (T_p^4 - T_{sky}^4) \quad (11)$$

where $\varepsilon = 0.95$ is the water emissivity in the infrared region, $\sigma = 5.67 \times 10^{-8}\ \mathrm{W/m^2\,K^4}$ is the Stefan–Boltzmann constant and the equivalent sky temperature T_{sky} is given by Eq. (12) (Rakopoulos and Vazeos, 1987):

$$T_{sky} = 0.0552 \cdot T_{amb}^{1.5} \quad (12)$$

2.3.3. Convective losses

Apart from the evaporative heat losses, convective heat losses are also important. In this case, the driving force for heat transfer is the difference in temperature between water and ambient air, as given by the following equation:

$$Q_{conv} = h_c \cdot A_p \cdot (T_p - T_{amb}) \quad (13)$$

where the convective heat transfer coefficient h_c is, upon first approximation, a linear function of wind speed w:

$$h_c = A + B \cdot w \quad (14)$$

Like in the evaporative losses, convection heat losses also depend on the wind speed, and assigning values to the parameters A and B is a delicate question too. The Australian Standard (1989) on solar heating systems for swimming pools proposes the correlation shown in Eq. (15) for evaluating h_c:

$$h_c = 3.1 + 4.1 \cdot w \quad (15)$$

In this correlation, the value of the coefficient B may be subject to discussion because of the question of the height at which the wind speed should be measured (Molineaux et al., 1994). The value of B in Eq. (15) corresponds to a reference height, and if the wind speed is measured at a different height, then parameter B has to be corrected. Nevertheless, the values given in Eq. (15) were used in the present paper.

As a final remark, Q_{conv} is not always a loss energy term, because it becomes negative when the ambient air temperature is higher than water temperature, which means that ambient air is actually contributing to pool heating.

2.3.4. Solar radiation gain

The pool receives its energy from solar radiation, with the water as well as the walls and the bottom of the pool absorbing a major part of this heat flux. The total energy absorbed in the pool can be calculated by means of the following equation:

$$Q_{sol} = \alpha \cdot A_p \cdot G \quad (16)$$

where A_p is the pool surface area, G is the solar irradiance and the effective absorptance α depends on different characteristics of the pool, such as its depth and colour of the bottom and sidewalls. The value of 0.85 recommended by ISO TC 180 (1995) was used in this work.

3. Results and discussion

Simulations were done for three different locations, based on real meteorological data. For all these locations, the predicted water temperature behaviour was analysed for different combinations of the model parameters. Different melting point temperatures were considered for the PCM in the pool walls and bottom, and also for the PCM contained in the heat exchanger.

3.1. Model validation

The registered pool temperatures and meteorological data obtained by Ruiz and Martínez were used in this work to validate the model. The temperature predicted by the model presented in this paper, and the registered temperature, were plotted on the same graph in Fig. 2. During all the period of three days, the differences between the simulated and the registered pool temperatures is less than 0.2 °C. The corresponding deviation can be calculated as the sum of squares of the differences between the simulated and the registered pool temperatures divided by the number of data. A value of 0.009 was obtained for the deviation, as calculated by Eq. (17), which confirms that there is a good agreement between the predicted and the registered temperatures:

$$\text{Deviation} = \frac{\sum_{i=1}^{N} (T_{i,sim} - T_{i,reg})^2}{N} \quad (17)$$

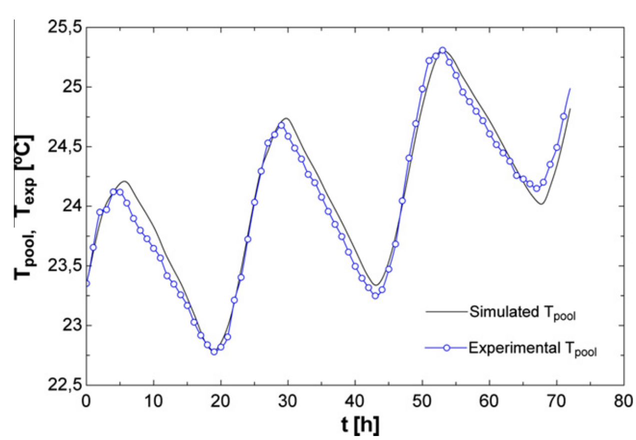

Fig. 2. Predicted and registered water temperatures.

3.2. Results for location 1: Gimenells

The first location corresponds to Gimenells, a small village situated at the west end of Catalonia, in the north-east of Spain, at an altitude of around 260 m. During summer, air temperature normally has high daily variations and the number of rainy days is quite small. The results obtained for this location are based on meteorological data taken from Meteocat (2011). These data are registered at a time interval of 1 h by means of an automatic station, which measures air temperature, relative humidity, wind speed and solar radiation at 2 m elevation from the ground. Data registered during the month of June of 2010 were used for the analysis, which in general is an adequate period for swimming pool usage, except for a few days when the weather may be too cold for bath.

Fig. 3 shows the results of the simulated water temperature evolution during the month of June of 2010. For this figure, the melting points of both PCM in the pool and in the heat exchanger were set to 23 °C and, at the initial time ($t = 0$ h) of this period, the heat exchanger was totally charged, i.e. the PCM in it was completely melted. One can observe from this figure that when the water temperature is around the PCM melting point, its daily amplitude in the presence of PCM is smaller than in the case of having no PCM. In this way, the height of the peaks is reduced when the temperature is above 24 °C, but it increases when the temperature is less than the melting temperature of 23 °C. The largest effect of PCM is observed in the time interval (300–400) h, when the temperature difference between the cases of using PCM and not using it reaches values as large as 1.5 °C. This effect comes from the combined action of the PCM in the pool and that in the exchanger. Nevertheless, one can also observe that after $t = 400$ h, this effect diminishes and even disappears at $t = 500$ h. This is because the exchanger released all its latent heat and the PCM in the pool is almost solidified and cannot release much more heat. Also the increase in the water temperature implies higher energy losses from the pool, so that after a relatively large period of poor

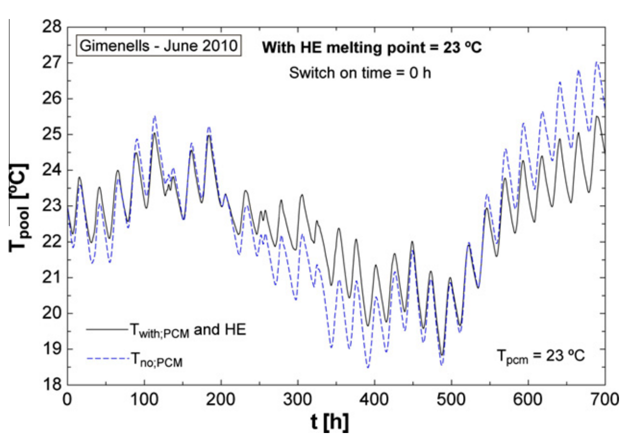

Fig. 3. Simulated pool temperatures for Gimenells. Both PCM in the pool and the heat exchanger have a melting point of 23 °C, and the heat exchanger is switched on from the beginning.

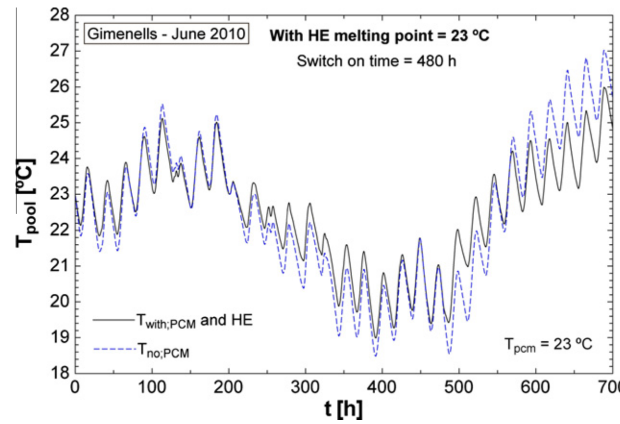

Fig. 4. Simulated pool temperatures for Gimenells. Both PCM in the pool and the heat exchanger have a melting point of 23 °C, and the heat exchanger is switched on at time $t = 480$ h.

weather conditions, the effect of PCM becomes insignificant. After time $t = 500$ h, the weather is improved and, consequently, water temperature increases. When it gets around 23 °C, the effect of PCM appears again, but this time it has the effect of slowing the increase in water temperature.

Fig. 4 shows the results of the simulations for the same melting point temperatures as in Fig. 3, with the difference that here the heat exchanger is initially switched off. In this case, for time $t < 480$ h, one can only see the effect of the PCM in the pool, which represents an increase of water temperature of about 0.5 °C with respect to the case with no PCM, in the interval (300–400) h. When the exchanger is switched on at $t = 480$ h, the next two temperature peaks are 1 °C higher than those corresponding to the case with no PCM. The effect of PCM disappears at around 24 °C, which may be considered a suitable temperature for bathing.

A step further was made to consider the situation in which there is no PCM in the pool, but only the heat exchanger with 23 °C melting point PCM, switched on at time $t = 480$ h. Fig. 5 shows the results in this case and one can observe that the temperature increases faster after $t = 480$ h than in the previous case, and the peaks of water temperature are 1.5 °C higher than in the case with no PCM. The PCM in the pool increases its thermal mass and part of the heat released by the exchanger is used to melt part of the PCM in the pool.

3.3. Results for location 2: Vall d'en Bas

The second location is Vall d'en Bas, situated at the north-east end of Catalonia, close to the Pyrenees, at an altitude of around 500 m. Here the air temperature in summer is lower than in the first location, but high enough for bath during the month of July and August. Also, air temperature may have rapid variations from one day to another and temperature during night may drop faster, which makes the use of a PCM storage system interesting.

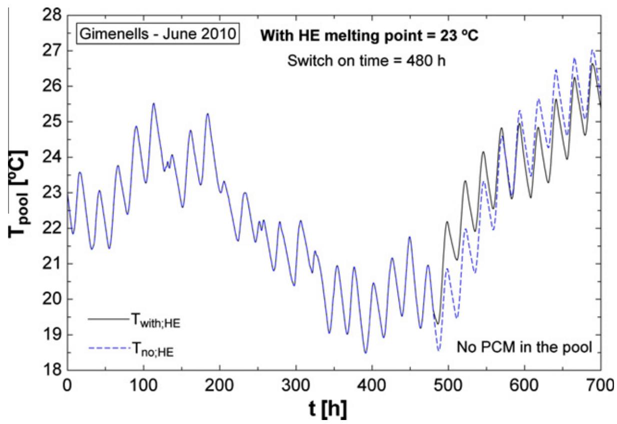

Fig. 5. Simulated pool temperatures for Gimenells. There is no PCM in the pool, but only the heat exchanger with melting point 23 °C and switched on at time $t = 480$ h.

Fig. 6 shows the results of simulations done for the entire month of June of 2010, where different melting points were set for the PCM in the pool and the heat exchanger. For a PCM melting point of 25 °C in the pool, one observes that it has negligible effect when T_p is around 23 °C, and when the heat exchanger having PCM with melting point of 23 °C is switched on (at $t = 470$ h), water temperature is almost 2 °C higher than in the case of no PCM, at $t = 500$ h. In this way, one can achieve comfort conditions earlier and increase the number of days for bath.

The effect of the PCM with melting temperature $T = 25$ °C can be seen in Fig. 7, for a two weeks period in July. One observes that during the first five days the effect of the PCM is to reduce the height of the peaks, but they remain around 25 °C which is a suitable temperature for bath. Then, after $t = 100$ h, there is an abrupt decrease in water temperature, and the presence of the PCM in the pool reduces the magnitude of this decrease and keep water at a higher temperature than in the case of no PCM.

Simulations were also done for the case in which only a heat exchanger with PCM melting point of 24 °C is used,

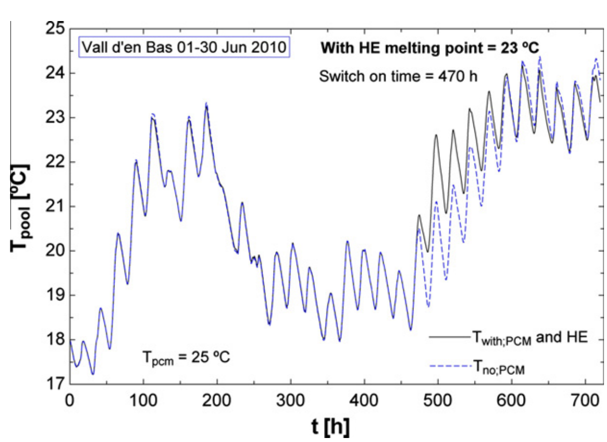

Fig. 6. Simulated pool temperatures for Vall d'en Bas. There is PCM with melting point of 25 °C in the pool, and also a heat exchanger with 23 °C melting point, switched on at time $t = 470$ h.

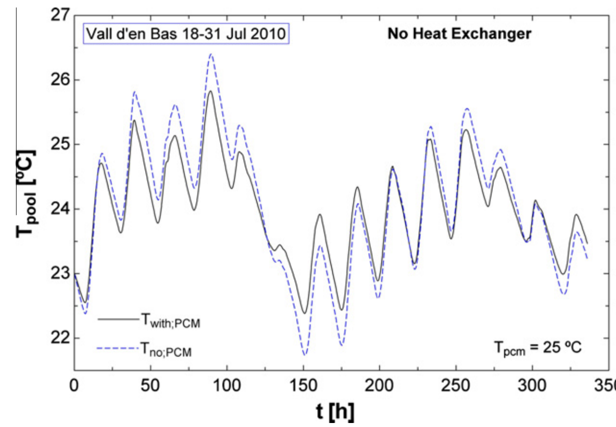

Fig. 7. Simulated pool temperatures for Vall d'en Bas. Only PCM with melting point of 25 °C is used in the pool, and no heat exchanger.

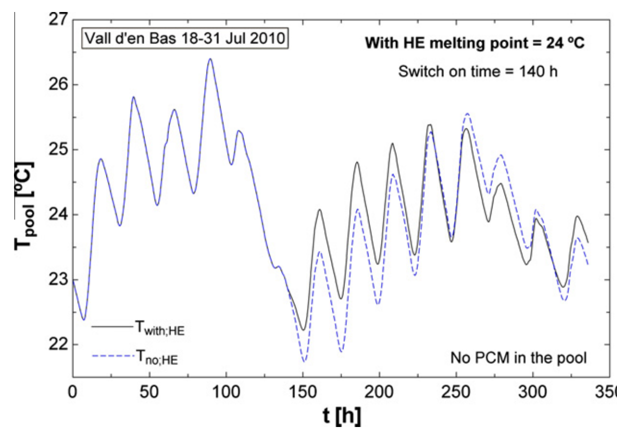

Fig. 8. Simulated pool temperatures for Vall d'en Bas. There is no PCM in the pool, but only the heat exchanger with 24 °C melting point, switched on at time $t = 140$ h.

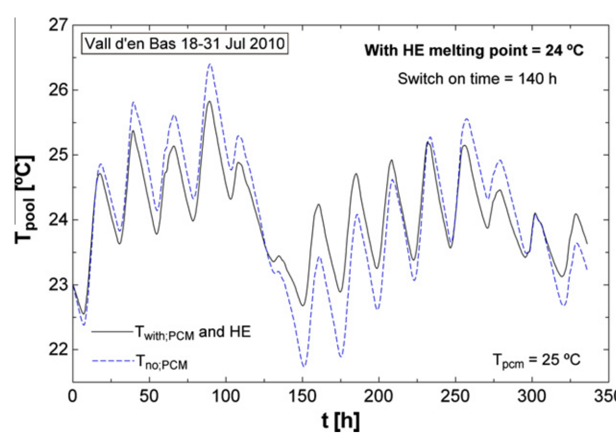

Fig. 9. Simulated pool temperatures for Vall d'en Bas. There is PCM with melting point of 25 °C in the pool, and also a heat exchanger with 24 °C melting point, switched on at time $t = 140$ h.

and with no PCM in the pool. Fig. 8 shows the results of these simulations, where the heat exchanger is switched on at $t = 140$ h. Compared with Fig. 7, one can see that using PCM in an external heat exchanger is more effective than having the PCM in the pool.

Fig. 9 shows the results of the simulation for the case in which PCM is used in the pool and in the heat exchanger. The results are similar to those shown in Fig. 8. The first peak after $t = 150$ h has a bit higher value than the corresponding peak in Fig. 8, but the following peaks seem to have similar or even lower values than in Fig. 8.

3.4. Results for location 3: Puigverd de Lleida

The third location, Puigverd de Lleida, is also situated at the west side of Catalonia and has similar climatic conditions as Gimenells. Existing data registered at the installations of GREA were used for simulations corresponding to different periods in spring and summer of 2009 (Cabeza et al., 2007, 2010; Castell et al., 2010).

The first simulations correspond to a period of 9 days at the beginning of May. Fig. 10 shows the results for a 25 °C melting point PCM in the pool and 23 °C melting point PCM in the heat exchanger, switched on at a time $t = 40$ h. Here too, the effect of increasing water temperature is due to the heat released by the exchanger, which makes it possible to have three days with a maximum water temperature above 22 °C.

The next period of two weeks was also simulated. Here again, it was considered that the PCM contained in the heat exchanger was initially melted. In Fig. 11 one can see that after the heat exchanger is switched on at $t = 70$ h, water temperature increases faster and gets to a peak value of 22 °C two days earlier than in the case of no PCM. It is interesting to notice that the effect of the exchanger disappears after six days, because of higher heat losses caused by higher water temperatures.

Fig. 12 shows the results of simulations for the period from 2nd to 19th of June. In this case, after the heat exchanger is switched on at $t = 160$ h, the water temperature remained 1 °C higher than in the case with no PCM during the next two days. After these two days, water reaches a temperature of 25 °C, at which the PCM has the opposite effect, since it is melting and absorbing heat back from the pool.

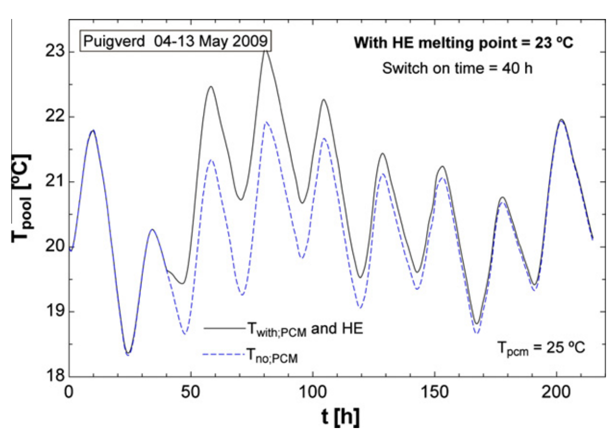

Fig. 10. Simulated pool temperatures for Puigverd. There is PCM with melting point of 25 °C in the pool, and also a heat exchanger with 23 °C melting point, switched on at time $t = 40$ h.

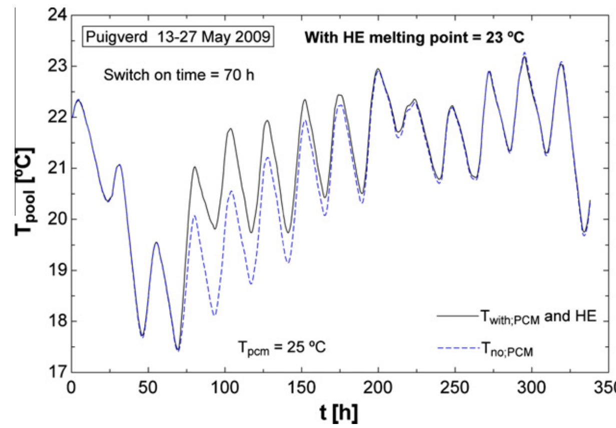

Fig. 11. Simulated pool temperatures for Puigverd. There is PCM with melting point of 25 °C in the pool, and also a heat exchanger with 23 °C melting point, switched on at time $t = 70$ h.

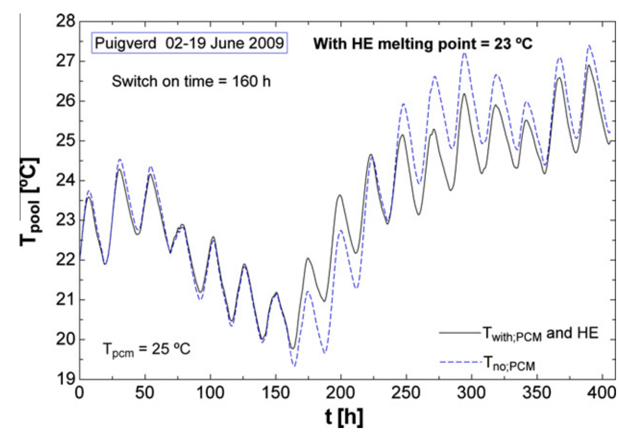

Fig. 12. Simulated pool temperatures for Puigverd. There is PCM with melting point of 25 °C in the pool, and also a heat exchanger with 23 °C melting point, switched on at time $t = 160$ h.

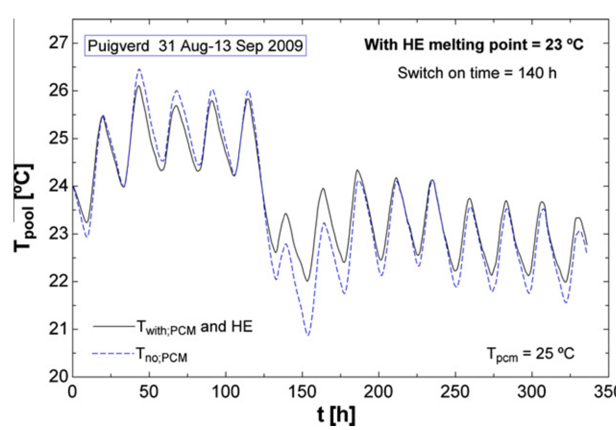

Fig. 13. Simulated pool temperatures for Puigverd. There is PCM with melting point of 25 °C in the pool, and also a heat exchanger with 24 °C melting point, switched on at time $t = 140$ h.

Finally, in order to see the effect of increasing the melting point of the PCM in the pool to 25 °C, simulations were done for a two weeks period at the beginning of September,

when the initial water temperature is somewhat higher than in the previous examples. Fig. 13 shows the results of the simulations for this period. The PCM melting point in the heat exchanger was set to 24 °C because otherwise no much effect could be observed. In this case, after $t = 130$ h, water temperature is always above the one corresponding to the case with no PCM.

In Fig. 14 one can observe that if there is no PCM in the pool, but only in the heat exchanger, water temperature variations are higher, but the peaks of the last days of the period are a bit lower than in the previous example in Fig. 13. This case is an example of situation in which using PCM in the pool becomes advantageous.

3.5. Discussions

The above results show that implementing a PCM storage system to an open-air swimming pool may produce an increment in the water temperature up to 2 °C, although for a limited number of days. This increment takes place during or after periods of poor weather conditions, such as low solar radiation, cold air temperature or high wind speed. On the contrary, when the weather is fine and the water in the pool is sufficiently warm for bath, PCM has the effect of reducing its temperature by absorbing the excessive heat, which may last a few days. This does not represent a problem because, when this happens, water temperature is in the comfort interval.

The PCM placed in the sidewalls and bottom of the pool has a positive effect when water temperature has a dropping tendency for a few consecutive days. For example, Fig. 15 shows that for Gimenells the maximum temperature of ambient air remains below 25 °C (except at $t = 300$ h) and bath becomes problematic because, as shown by Hahne and Kübler (1994), people do not use the pool during periods of poor weather conditions.

Using PCM in the walls and bottom of the pool increases its thermal mass and, as a result, the amplitude of daily temperature fluctuations is lower. It means that, generally,

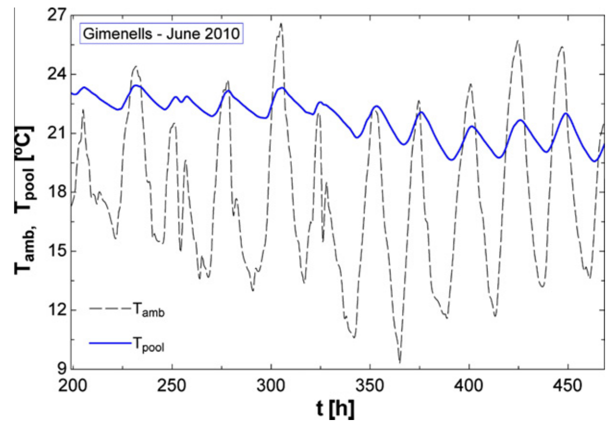

Fig. 15. Ambient air and simulated water temperatures for Gimenells.

water temperature is lowered during the day and increased during the night. This may make the swimming pool suitable for use at night.

In principle, an increase of the mass of PCM in the heat exchanger should produce an increase in its heat storage capacity and, consequently, more effect on the temperature. Fig. 16 shows the results of water temperature behaviour for Gimenells, in the case of having an infinite thermal capacity. The graph shows that in the presence of such a large PCM *reservoir*, the maximum temperature gain is about 2 °C in the period when the water is colder ($t \approx 400$ h), and it diminishes when bath conditions start to appear ($t > 500$ h). By comparing these results with those shown in Fig. 5, one can see that a heat exchanger with a finite storage capacity of $Q_{HE} = 7.5 \times 10^8$ J is sufficient to produce the effect needed to achieve comfort conditions at the proper moment.

The efficiency of the heat exchanger depends on its heat transfer characteristics. An increase in the value of $U_{he} \cdot A_{he}$ implies an increase in the efficiency of the heat exchanger, which has the effect of improving the rate of heat transfer between the PCM and the water. This has the advantage of reducing the discharging time of the stored heat or,

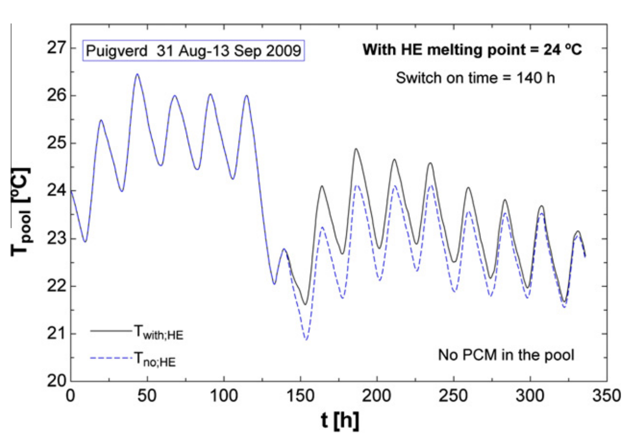

Fig. 14. Simulated pool temperatures for Puigverd. There is no PCM in the pool, but only a heat exchanger with 24 °C melting point, switched on at time $t = 140$ h.

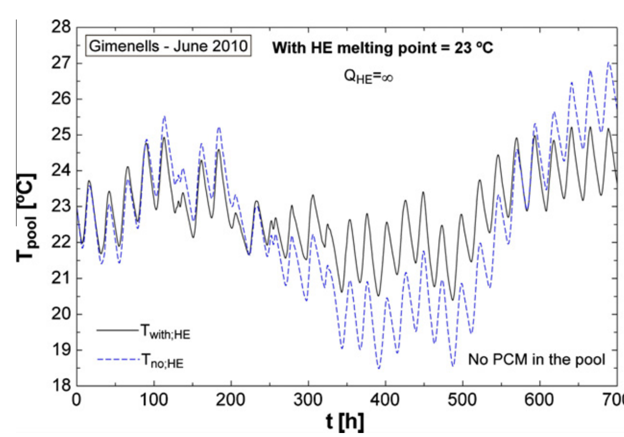

Fig. 16. Simulated pool temperatures for Gimenells. There is no PCM in the pool, but only a heat exchanger with infinite thermal capacity and melting point of 23 °C.

equivalently, producing more effect on the water in a given period of time. The authors consider that the value of $6000\ \mathrm{W\ C^{-1}}$ for $U_{he}{\cdot}A_{he}$ is a reasonable value for a heat exchanger of the characteristics of this work, which gives an efficiency of the heat exchanger ε of about 0.78.

Another way in which the heat transfer rate from the heat exchanger to the water can be increased is by increasing the PCM melting temperature. Then, even a lower value for $U_{he}{\cdot}A_{he}$ could be allowed without affecting the performance of the heat exchanger, and would probably cheapen the cost of it. An interesting choice would be a PCM melting point around 29–30 °C, which would imply a faster heating rate of the water and also the possibility of preventing water overheating during hot periods in summer, when a too high water temperature may be undesirable. Thus, when the heat exchanger is used for cooling, the PCM is melted by the water, and the stored heat can be used later for heating the water. Otherwise, when the heat exchanger is used for heating the water outside the hot period in summer, an auxiliary source of heat is needed, such as solar collectors, in order to melt the PCM.

As mentioned in Section 2.2, similar amounts of PCM were considered in the two different ways in which PCM was implemented in the swimming pool. Thus, when the PCM is encapsulated in the sidewalls and at the bottom of the pool, the minimum thickness of the PCM layer needed to produce a 2 °C increase of the water temperature is about 3 cm. In order to find out if a thicker layer of PCM would be beneficial or not, a further study was done, in which different thicknesses of the PCM layer were considered. In that study, the temperature evolution of the last node T_{20} of the PCM layer at the bottom of the pool was simulated for periods when the water temperature dropped at least 4 °C crossing the temperature range of the phase change process. If the temperature of this last node also drops about 4 °C and achieves a value close to that of the end of the solidifying process, it means that practically all the PCM has solidified and all its latent heat has been released.

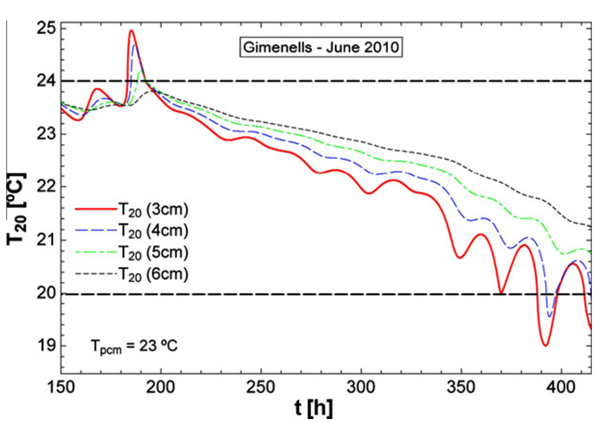

Fig. 17. Temperature T_{20} of the last node of the bottom PCM layer, for different thickness values. Simulations are done for Gimenells considering a PCM melting point of 23 °C.

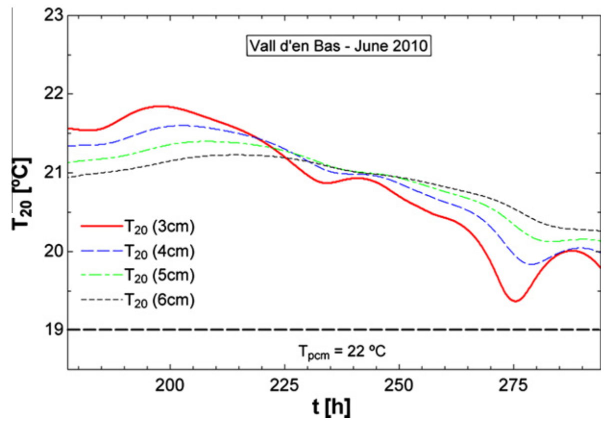

Fig. 18. Temperature T_{20} of the last node of the bottom PCM layer, for different thickness values. Simulations are done for Vall d'en Bas considering a PCM melting point of 22 °C.

In Figs. 17 and 18 the temperature of the node 20 is represented for different values of the thickness of the PCM layer, during periods when the water temperature dropped at least 4 °C, corresponding to simulations done for Gimenells and Vall d'en Bas, respectively. In Fig. 17 one can appreciate that after the descending tendency finishes at $t \approx 400$ h, the PCM layer is completely solidified when its thickness is 3 cm or 4 cm, and it is only partially solidified for higher thicknesses. This means that, in the case of this particular example, even a 4 cm layer of PCM would be appropriate for heating the water. On the other hand, in Fig. 18 one can see that at the end a period when the water temperature decreases by more than 4 °C ($t \approx 275$ h), even a 3 cm thick PCM layer is too large to allow all the PCM to solidify. One can also notice that, at the initial moment, the PCM layer is not entirely melted since T_{20} is less than 23 °C, which is the point where the melting process completely ends. Thus, even the minimum thickness of 3 cm, needed to produce a potential 2 °C increase of the water temperature, may not always be totally exploited, and a higher thickness would be even less beneficial.

From the results shown in this work, one can conclude that using a PCM heat exchanger rather than using PCM in the pool walls and bottom has two important advantages: (1) one has the control of the moment when the latent heat stored in the heat exchanger should be released, and (2) the heat exchanger is more efficient from the point of view of the heat transfer rate. One could improve the rate of heat transfer of the PCM in the pool by increasing its thermal conductivity, so that melting and solidifying processes could occur faster, but one is limited by the convection heat coefficients h_{wall} and h_{bott} between water and the walls and bottom surfaces, respectively.

As compared to other more common pool heating options like simple, cheap solar collectors coupled to a pool cover, the use of an external PCM heat exchanger has the following advantages: (1) one can control the time when the stored heat may be released; (2) it has no visual impact and it causes no space problems because the heat exchanger

may be buried under ground; (3) it does not produce overheating of the pool during the hot periods in summer, and (4) the swimming pool may be used anytime, even during night, while when the pool is covered bath is not possible.

4. Conclusions

The effect of a PCM storage system on the thermal behaviour of an open-air swimming pool was studied by simulations using meteorological data for distinct periods and for three different locations, after it has been validated against some experimental measurements.

Two ways in which PCM could be implemented in the swimming pool were considered: (1) encapsulated in the sidewalls and at the bottom of the pool and (2) in an external PCM heat exchanger.

The simulations showed that the first way of implementing PCM in the pool was not very efficient. It produced some positive effect on the water temperature during periods when it was dropping. But this effect might not be useful because during those periods the weather conditions may not be suitable for people to use the pool. On the other hand, using an external heat exchanger filled with PCM showed a better effect, especially due to the possibility of controlling the time at which heat is to be discharged.

The principle of using PCM in a heat exchanger is more suitable and easier to design. It gives the benefit of delivering its heat content at any desired time.

An efficient way in which the heat exchanger can be "charged" is by using solar collectors as an auxiliary source of energy. Nevertheless, such a study of integrating the PCM storage system with any other alternative heating system is beyond the objectives of this work.

Acknowledgements

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